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TECHNICAL ARTICLE

Application of Geo-electrical Tomography in Coupled Hydro-mechanical–Chemical Investigations in Heap Leaching

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Abstract
A shortcoming of the heap leaching process is its inherent limited metal recovery rate, due primarily to preferential pathways, which reduces the efficiency of the leaching process and can decrease the stability of the heap structure. In this study, geophysical methods were used to characterize the heaps. Five geophysical profiles with 10 m electrode spacing were created on the Miduk heap leaching operations in Iran using mixed array electrode spacing. The dipole–dipole data preserved the high resolution of the surficial response while the dual-direction pole–dipole arrays data provided the desired depth range of 50 m. The inversion of geophysical data revealed areas of focused fluid flow within the heap structure as well as zones of high and low moisture content, and hence areas with a risk of structural failure. In dry zones, under high matrix suction, the hydraulic conductivity is less than in zones with higher water content; thus flow is preferentially focused within the wetter zones, inducing leakage. Geo-electric data also revealed that the three initial heap lifts (oxide lifts) adjacent to the liner were almost impermeable to the leaching fluid due to their fine-grained nature and their high clay content. Oxide materials react more with acid and their structure degrades over time, leaving finer size particles with less permeability. Low permeability zones can cause preferential fluid pathways and pooling to develop elsewhere in the heap, followed by the loss of metal content in those areas. The relationship between these zones is governed by the relative differences in hydraulic conductivity (k) as a function of the water content and matrix suction. If the fluid flux rate is less than the K_{sat} (saturated hydraulic conductivity) of the fine materials, most of the flow will pass through the fine materials. Therefore, local injection of fluid and changing the fluid flux rate in problematic zones has been suggested. Correlations between resistivity and parameters such as fluid accumulation, copper grade, and slope stability, can be indirectly used to determine the important operational parameters of the heap leaching structures.

Keywords Heap hydrogeology · Mixed array electrode spacing · Preferential flow · Hydraulic conductivity · Pooling · Miduk Copper Mine

Introduction

Optimum performance of an ore leaching process depends on various parameters, including ore mineral type, comminution properties, fluid injection rate, heap permeability properties and flow rates, liner characteristics, and process time (Watling 2006). Such a complex system makes leaching a coupled and multi-factorial process. Thus, column leaching test results cannot be easily generalised to large-scale leaching operations. Normally, metal recovery efficiency in the field is much less than in controlled lab tests. Indeed, in most cases involving fluid flow in geological media (such as petroleum reservoir exploitation, geothermal energy extraction, environmental hydrogeology, and waste transport in mining environments), coupled interactions and potential chemical issues must also be considered in addition to the physical and mechanical processes. Moreover, the thermal energy produced by such chemical reactions and the resultant temperature change further complicates our understanding and ability to control such processes. Heap leaching is also a process in which the simultaneous effects and interactions of the geotechnical, chemical, and rheological properties of the

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solid/fluid medium result in significant challenges in trying to understand its behaviour.

Development of preferential pathways for fluid flow is the most significant problem in a heap leaching process because these pathways can significantly reduce the metal content of the final pregnant leach solution (PLS); furthermore, these pathways increase the risk of leakage and total failure of the heap structure due to the concentration of fluid (or "pooling"). Although up-scaling of heap leach column tests to operational scale has proved challenging, global research has continued to improve the recovery and efficiency of the heap leaching process. For example, Petersen and Dixon (2007) developed a software package named "HeapSim" for modeling, analysis, and simulation of heap leaching, and applied it to actual field cases. Additional research has been done on heap leach modeling and simulation, and some of them used CFD (computational fluid dynamics) to model the leaching process (Cross et al. 2006; Groznov 2015; McBride et al. 2012a, b; 2016; Watling et al. 2017). Also, Ghorbani et al. (2011) reviewed the effect of the presence of large particles on fluid flow through a heap structure.

Wu et al. (2010) also conducted extensive research on hydrogeology within heap structures and specifically on the topic of preferential pathways. For example, they investigated the concurrent effects of chemical activity and rheological properties of the fluid on heat transfer within bioheap structures, and simulated the concentration of copper, iron(III), and oxygen, as well as the internal temperature distribution. Wu et al. (2007) also led one of the first studies on preferential fluid pathways in heap leaching operations in China. They studied two distinct ore samples that included fine- and coarse-grained copper ore. By performing several heap leaching column tests, they investigated the influence of particle size on the probability and frequency of preferential pathways.

Wu et al. (2009) investigated the effect of preferential paths on copper extraction and surficial morphology of copper sulphides. Also, Yang et al. (2012) and Yin et al. (2013) carried out extensive research using CT-Scan images to model the leaching process, and simulated acid flow into materials containing copper.

Sarcheshmehpour et al. (2009) examined the influence of clay particles on heap bioleaching at the Sarcheshmeh copper mine, Iran. Their results showed that the oxidation–reduction potential in the heap decreased due to the presence of clay particles and that the clay minerals also increased the pH of the pore water and decreased the amount of sulphur- and iron-oxidizing bacteria. Moreover, the low permeability of the clay-rich zones in the heap created pooling zones and reduced copper, recovery.

These past studies were mostly focused on determining how preferential flow paths form and how they affect the heap leaching process. The key point regarding the leaching process is that in practice, factors such as particle grading during truck loading and mineral heterogeneity of feeding loads create preferential flow paths in a three-dimensional heap, so that laboratory and modeling results are usually quite different from reality. Therefore, other approaches are required. For example, Rucker et al. (2009) applied geophysical methods to detect subsurface heap leaching structures in Nevada, USA. In another study, Rucker (2015) proposed the "rinsing well" method to detect unleached locations in the pile as a potential way to improve the heap leaching process.

Although geophysical methods have not often been used in heap leaching studies, they have been used for mine tailings, either for re-treatment in mineral processing or for environmental purposes. Among these studies, Günther and Martin (2016) used spectral induced polarization (SIP) and resistivity (RES) to characterize tailings material. Shokri et al. (2016) and Shafaei et al. (2016) examined the environmental aspects of wastes produced by coal washing operations at the Alborz Sharghi plant, in northeast Iran. In another study, Moradipour et al. (2015), used RES and ground penetrating radar to investigate old heaps of the Sarcheshmeh copper mine to detect locations containing residual copper. The geophysical responses extended to an approximate depth of up to 20 m, below which array limitations prevented the acquisition of deeper signals.

In this study, two main issues were addressed at the Miduk copper mine in Iran: (1) leakage from the heap walls and instability of the heap leaching structure, and (2) development of preferential flow paths and resultant low-grade PLS and increased acid usage. The RES and IP methods were implemented using various geophysical arrays to investigate simultaneous effects of hydrogeological, chemical, and mechanical factors on the heap leaching structure. In addition, geochemical studies were carried out for further analysis and comparison of results.

Heap Structure and Thermo-hydro-mechanical–Chemical Coupling

Heap leaching is a common hydrometallurgical method in copper extraction in which the excavated ore is transferred onto a leach pad. Before heap construction, a base (bed) is constructed, which consists of a layer of clay, fine grained soil, and a geomembrane liner (Majdi et al. 2007). Copper ore is deposited on the heap structure, creating lifts of 5–8 m. In the next stage, special emitter pipes are installed on each lift for acid injection irrigation, which extracts the metals from the ore. Depending on the ore mineralogy, different chemical reactions may take place in the heap (Davenport et al. 2002). The PLS, is then transferred to solvent extraction (SX) and electrowinning (EW) plants to produce cathodic copper. Figure 1 illustrates the schematic stages of copper extraction in a hydrometallurgical system.

Metal extraction efficiency can be significantly affected by flow path geometry within a heap. As shown in Fig. 1, preferential flow can develop in the heap from mineral dissolution and transformation reactions, heat liberation during these reactions, and from heterogeneous material granulometry due to truck loading and dumping. Preferential flow paths may also develop from other mechanisms including macropore flow, fracture flow, funneled flow controlled by macroscale heterogeneities, fingered flow controlled by hydraulic instability (Nimmo 2012), and pooling within the heap structure. These preferential paths are extended during subsequent heap loadings and irrigations, creating a complex structure. They can form at the micro-scale due to spatial differences in moisture content or at the macro-scale due to spatial differences in hydraulic conductivity. Preferential flow paths also contribute to non-linear behaviour (Kolditz et al. 2015), for example by leading to greater contrasts between low and high flow rates, and by forming high concentration or temperature gradients and sharp reactive fronts. Hydraulic and mechanical parameters such as porosity, permeability, and shear strength, may also change during reactive transport within complex non-linear flow systems. Such changes in parameters, including temperature, may also affect the governing chemical reactions (Steefel et al. 2005). Most of these coupled processes have been studied over the past several decades, in particular within the context of the global Decovalex model-benchmarking project (Chan et al. 1995). Heap leaching is considered a coupled process due to its multifactorial characteristics and the non-linear effects of multiple phenomena (Fig. 2).

In contributing to preferential flow, some factors can reduce metal recovery while others can cause geomechanical

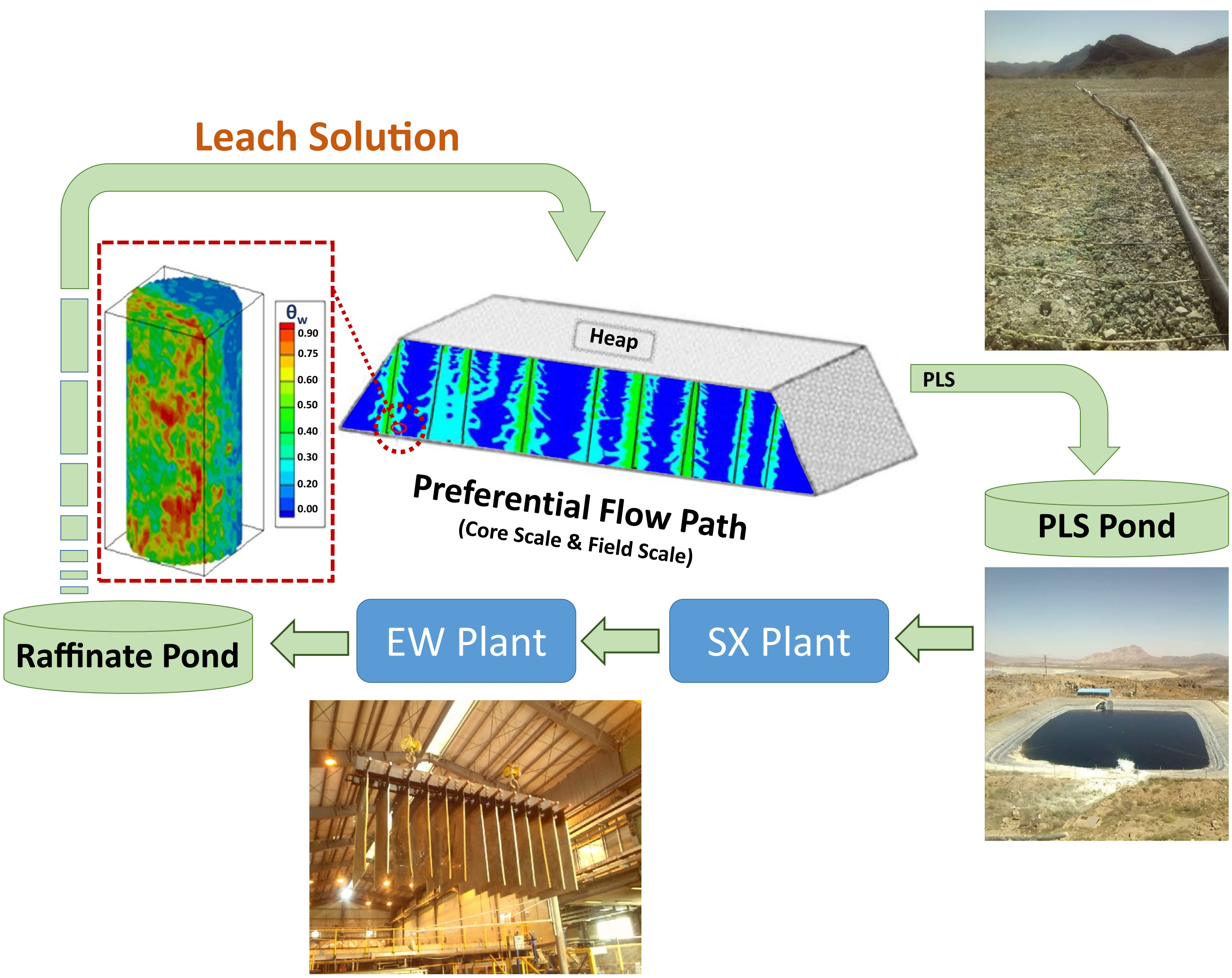

Fig. 1 Schematic representation of the main components of the heap leaching process that also shows the preferential flow path concept at the core scale and field scale

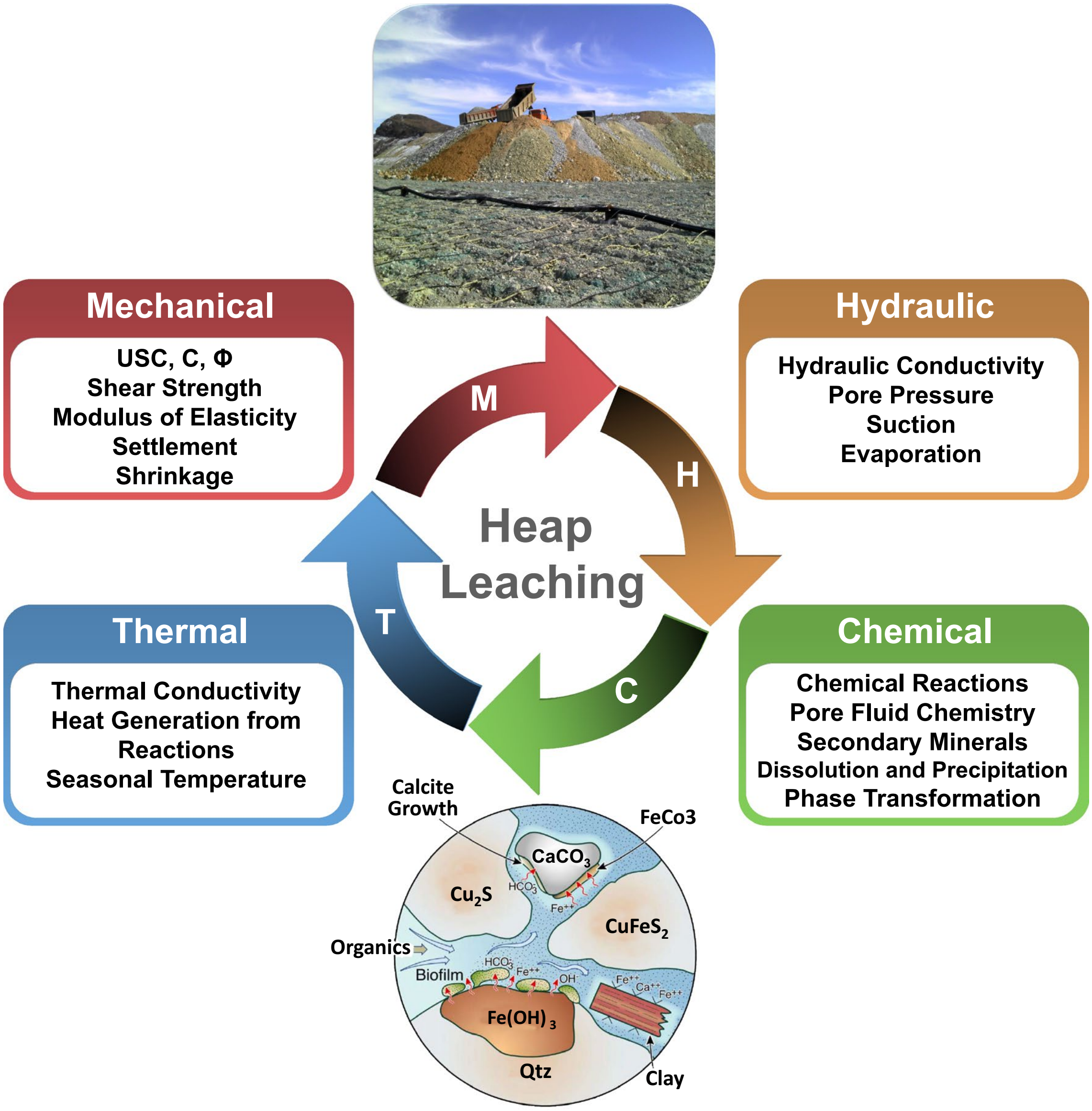

Fig. 2 Schematic showing the heap leaching process as a coupled thermo-hydro-mechanical–chemical (THMC) phenomenon, with lists of controlling parameters and governing processes

problems. Thus, preferential flow needs to be detected directly in the field for successful operation of large heap structures. Noteworthy field experimental studies of preferential flow paths include McBride et al. (2016), O'Kane et al. (1999) and Wu et al. (2007). Detecting and characterizing preferential flow paths can also be used to define the optimal irrigation discharge rate on the heaps (Mellado et al. 2011).

The tripartite relation between granulometry, volumetric water content and unsaturated hydraulic conductivity (Fig. 3), specifically illustrates how moisture content and unsaturated hydraulic conductivity (K_{uns}) vary with matrix suction for two types of soil. Figure 3 also shows that if the irrigation rate is greater than the saturated hydraulic conductivity of the fine grain material (point F in Fig. 3a), at a specific degree of matrix suction (cross-over of curve in Fig. 3a), the K_{uns} of the coarse material becomes less than K_{sat} and K_{uns} of the fine material, then the water will preferentially pass through the fine materials instead of the coarse material (contrary to expectation). As shown in Fig. 3b based on the O'Kane et al. (1999) study, if the fluid flux is greater than the K_{sat} of the fine material, most of the flow will pass through the coarse materials, while if the flux is less than the K_{sat} of the fine materials, most of the flow will pass through the fine materials.

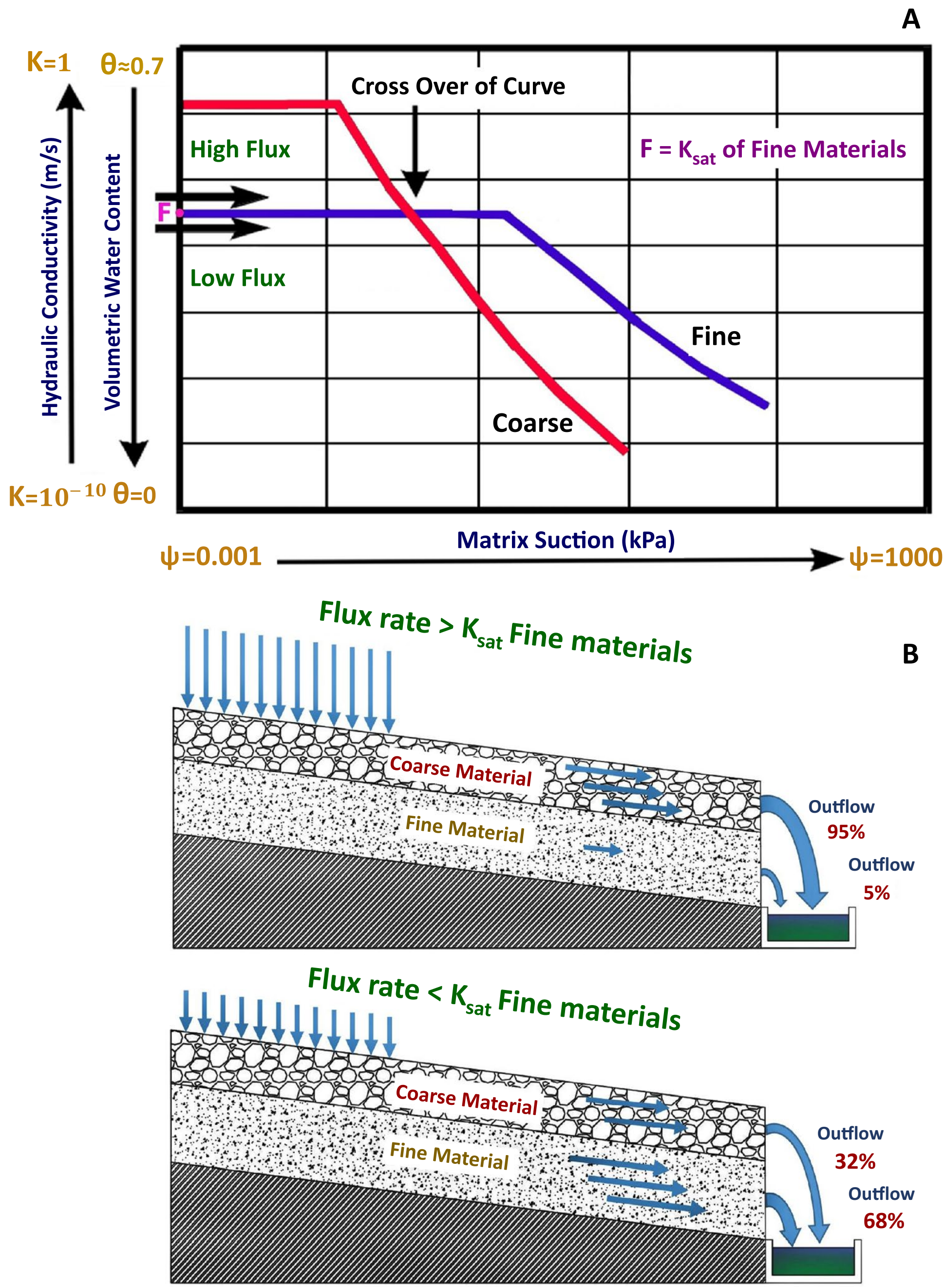

Fig. 3 Tripartite relation between granulometry, volumetric water content and unsaturated hydraulic conductivity (**a**) and the effect of flow rate on the flow paths within the materials (**b**). [Modified after (McBride et al. 2016; O'Kane et al. 1999)]

The concepts illustrated in Fig. 3 highlight how preferential flow paths can develop in a heap. Furthermore, considering the non-linear coupling between moisture content (matrix suction) and unsaturated hydraulic conductivity, accurate measurements of the moisture content in the heap can be critical for characterizing heap leaching processes. Hydrogeophysical surveys can be very useful tools for estimating subsurface hydrodynamic parameters including moisture content, which can then be used in numerical models to simulate preferential flow in heap leach piles. Developing such optimised models and determining irrigation rates provides an opportunity to improve heap leaching recovery.

Study Area: Miduk Copper Heap Leaching

The Miduk mine is one of the largest open pit copper mines in Iran, and is projected to be one the deepest mines of the country in the near future. The mine is located 132 km northwest of the Sarcheshmeh copper mine in Kerman Province. Miduk is a mountainous area 2842 m above sea level at a latitude of 30.25 °N and longitude of 55.10 °E. The Miduk mine has a reserve of 171 million tonnes (t) of copper at an average grade of 0.83%. The main lithological units in the area are volcano-clastic rocks (andesitic and basaltic), limestone, and sandstone of Eocene age. The Miduk deposit is composed of three main lithological units: volcanic (andesite, andesi-basalt and volcano-clastic tuffs), sedimentary (red sandstones), and plutonic (altered porphyritic diorites and dikes). The mineralization in the Miduk mine occurs in porphyritic diorite rock and the waste rocks are mostly andesite. Annually, leaching at the mine produces 4500 t of cathodic copper, and about 10 million t of ore are loaded onto the heap every ≈ 10 years. The average grade of ore materials in the heap is about 1% for oxide ore and 0.4% sulphide ore. The three initial lifts of the heap consist of oxide ores while subsequent lifts contain a mixture of sulphide and oxide minerals. The rock at the base of the heap structure is a slightly altered andesite that has a relatively high mechanical strength. The groundwater level is relatively deep below the heap structure, but in some places, the primary piezometers have shown water levels at depths of about 4 m below the ground surface. The location of the mine pit and an aerial photo (Google Earth) of the mine's leaching complex is shown in Fig. 4.

Heap Characterization

The Miduk heap leaching complex was first designed for low-grade oxide minerals. However, a decrease in tonnage and the grade of these materials led to the use of low-grade sulphide ore instead of oxide ore for the heap leaching process. Heap No. 1, which is the active heap of the Miduk complex and on which the current study was implemented, comprises 14 pads that are located on two rows (Fig. 4) with a north–south trend and a dip of 7° towards the PLS pools in the northern part of the heap. The average height of each lift in each pad is about 5–6 m and there are between 4 and 11 lifts in each pad. The feeding loads on the lifts are transported from two dumps: oxide dump 2, and sulphide dump 7. Dump 2 is divided into two parts: low- and high-grade ores. Mineralogical characteristics and average grade of the two main feeding dumps of 2 and 7 were determined by sampling, mineralogical studies, and examination of thin and polished sections. The results are given in Table 1. Differences in mineralogy between dumps 2 and 7, including the amount of clay minerals and the reaction rate with sulphuric acid, induced differences between the geophysical and hydrodynamic parameters of the first three lifts of each heap with respect to the other lifts.

Supplemental Figure S-1 shows photo-micrographs of thin and polished sections of a sample from the high-grade part of dump 2. As shown, quartz (qtz), feldspar (feld), and sericite (ser) are the most common non-metallic minerals. Pyrite (py) and chalcopyrite (cp) are the main metallic minerals, though malachite (mal) is also present.

Another important issue in the basic thermo-hydrodynamic investigation of heap leaching processes is grain size distribution and heap saturation time. These two parameters significantly affect the hydro-mechanical and chemical behaviour of a heap, and can affect the creation of preferential flow paths and change heap recovery.

Optimum grading and irrigation frequencies are commonly estimated through the use of column tests, even though, in practice, these column tests are not able to reproduce the real behaviour of the heap over time, and field-scale heap recovery is always much lower than predicted in laboratory tests. Column tests are also not able to reproduce other phenomena that occur during the heap operation, such as formation of preferential flow paths, wall instability, leakage, and fluctuations in the grade of the output PLS.

Accordingly, to better understand heap behaviour, a series of resistivity measurements on the input feeding ore was necessary to investigate resistivity variations and to compare the results with laboratory tests. Laboratory resistivity measurements of the Sarcheshmeh mine ore, which is very similar to the Miduk ore, are shown in Fig. 5. In this study, two industrial sand and sulphide copper ore samples were saturated with sulphuric acid over different time periods and with different grading ranges (Moradipour et al. 2013). As shown in Fig. 5, the resistivity of copper oxide soil is much less than that of ordinary soil or silica sand. Compared to sulphide ore, the resistivity of silica sand is higher at a similar level of saturation, and increases almost steadily with grain size, reaching a maximum resistivity at a grain size of 2.25 mm. At grain sizes above 2.25 mm, resistivity decreases linearly. However, the sulphide ore shows a different trend. The resistivity increases with grain size and reaches a maximum at 1.75 mm. Resistivity then decreases linearly between a grain size of 1.75 mm to about 2.20 mm, remaining constant for larger grain sizes. It is important to note that in a field-scale heap, the retention time and operational costs increase with decreasing grain size. Determining an optimum grain size using electrical resistivity is therefore an important task during the design stage of a heap.

Geophysical Surveys and Calibration

Electrical tomographic studies were conducted along with IP surveys incorporating three different arrays in order to investigate the heap operational conditions at the Miduk copper mine. The main goals of these studies were to: (1) determine the fluid flow behaviour below the heap structure and identify preferential fluid flow paths, (2) detect locations of residual copper, and (3) detect

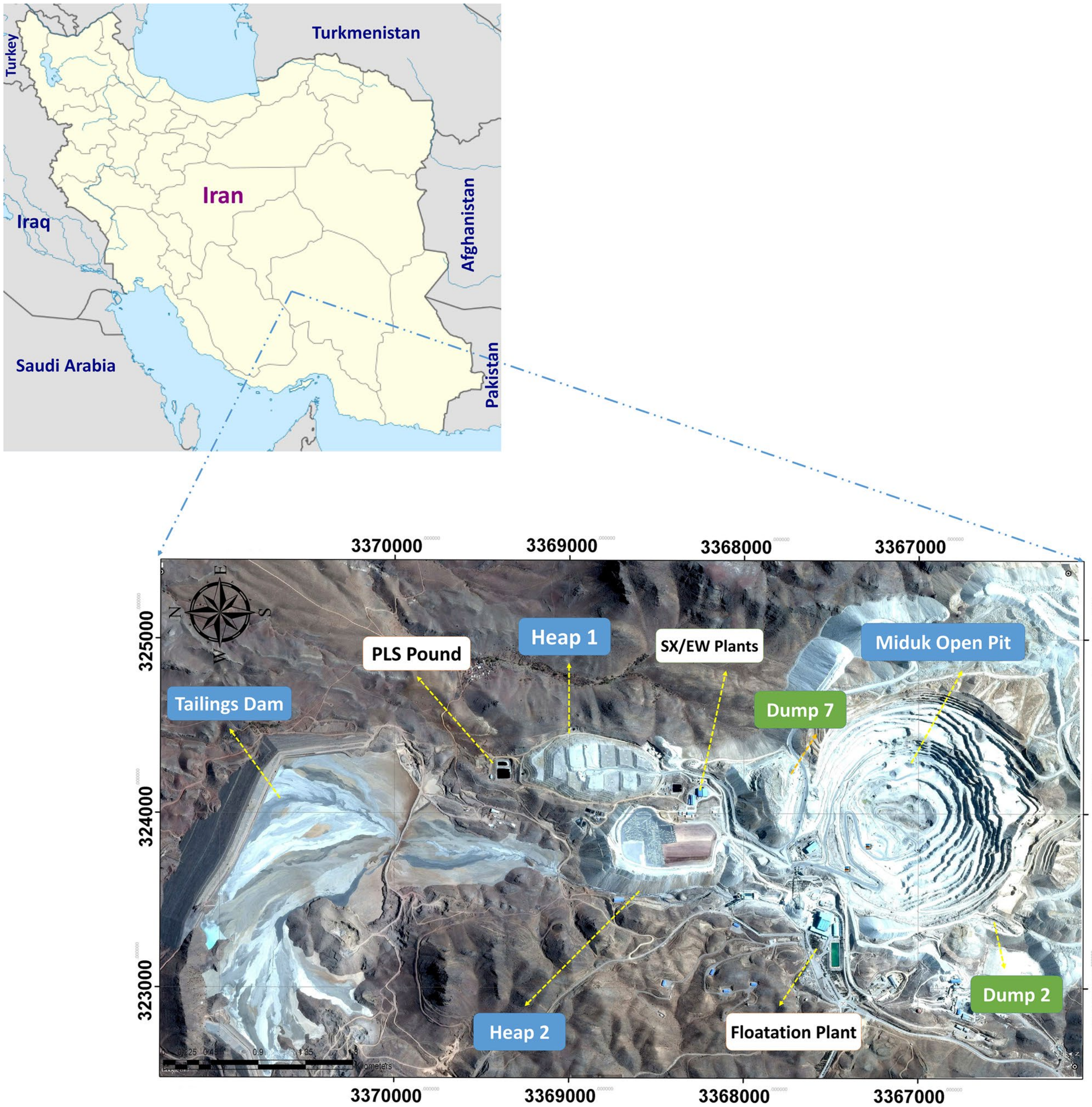

Fig. 4 Geographical location of the Miduk open pit mine, waste dumps, leaching facilities and tailings dam

leakage zones and areas of high moisture content that could lead to instability. Five geophysical profiles were created (Fig. 6), using three geophysical arrays comprising dipole–dipole, pole–dipole, and Schlumberger arrays. The results from two of the RS and IP methods are presented here. In total, resistivity was measured at 4000 measuring points. As the heap structure is made of rock fragments and coarse-grained particles, and considering the fact that the electric current cannot easily enter the heap, 1.5 m long special steel electrodes normally used in geotechnical investigations were applied in this study to reduce contact resistance with surface soils (Fig. 7). The geophysical equipment used in the study was a GDD brand, model GRx8-32 Receiver and TxII Transmitter, made in Canada (Instrumentation GDD Inc.) and owned by the University of Tehran. This equipment is extremely robust for such environments, with a power of about 3500 W, a maximum current of 10 A, and an output voltage of 200 V. During the field investigations, the current penetrating into the ground was about 5 A.

Table 1 Mineralogical results from the feed dump samples (mineral percentages are given in volume fractions)

Dump	Sample	Thin section results	Polished section results	Cu, %
7	7A 7B	75% muscovite, sericite, quartz 25% residual amphiboles and clays 5–7% clay (mostly kaolinite) 1–2% chlorite 2–3% metallic minerals	3–4% metallic minerals 3–4% pyrite Chalcocite is more abundant than chalcopyrite Sample is low-grade sulphide ore with a high fraction of pyrite There is no covelite or sphalerite	0.2
2 Low grade	2NA 2NB	20–30% quartz 40–45% clay minerals with altered feldspar 10–15% opaque minerals and Fe hydroxides 15% sericite and muscovite 2–3% metallic minerals 20–25% clay minerals	Most metallic minerals are replaced with Iron hydroxide Chalcopyrite is about 0.01% There is no chalcocite or magnetite Pyrite is about 0.1% Sample contains a stockwork system and silicified veins	0.06
2 High grade	2MA 2MB	20–25% quartz 25–30% feldspar in semi-altered form 20–25% clay minerals 15–20% sericite and muscovite 2–3% malachite and azurite	Pyrite is about 0.01% Some limited chalcopyrite in free and aggregate forms Two or three small grains of chalcocite in free form	2.66

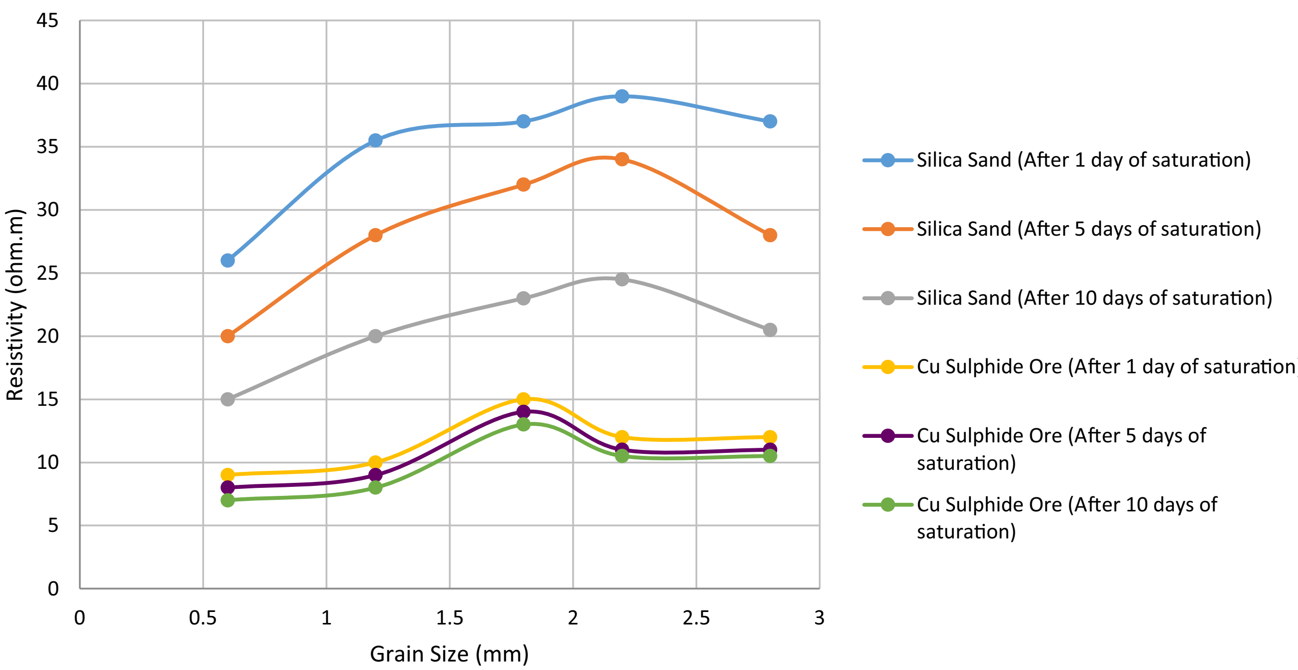

Fig. 5 The effect of time, material properties and grain size on the resistivity of soils under H_2SO_4 saturation; Modified after Moradipour et al. (2013)

The location of geophysical profiles and soundings on the heap surface are shown in Fig. 6. Moreover, Fig. 7 shows the area of interest, profile orientations, and electrode locations. The electrode spacing in each pole–dipole and dipole–dipole array was 10 m. To confirm repeatability and to determine the required resolution of the arrays, a profile of 5 m length was also completed on Pad 5, applying both arrays (see Fig. 6). Furthermore, to evaluate the system's accuracy, a Schlumberger-type resistivity surveywas conducted at the intersection of profiles P2 and P3 on Pad 5 (Fig. 6). To determine the resistivity of ores on the heap before acid irrigation, the geophysical profiles were designed in such a way that they sampled some parts of lift 5 of Pad 3 that was being loaded (Fig. 7). Depending on the array type, the data collected in each measurement refers to a certain point of the ground under investigation. An inversion process is applied to convert the measured apparent resistivities to real resistivities.

Field investigation of the eastern slope of the Miduk heap revealed a high amount of moisture originating from the

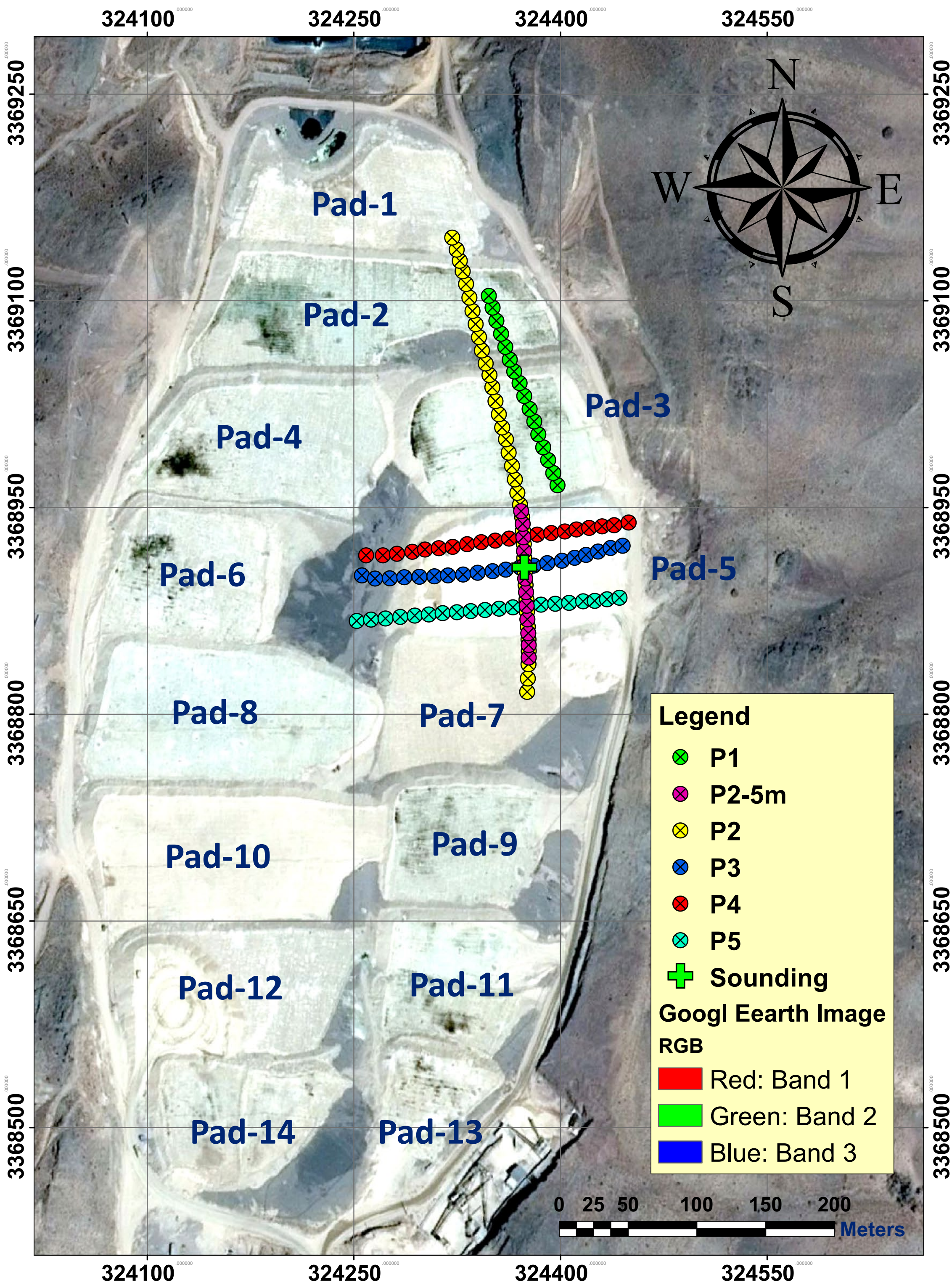

Fig. 6 Position of geophysical profiles and sounding locations on the heap surface

fluid behind the slope. This was more obvious in lifts 4 and 5. The border between Pads 2 and 3 shows leakage of copper-bearing solution from the slopes due to acid irrigation of Pad 3, especially during the winter season (Fig. 8). This fluid flow is directed downstream beneath the heap and is collected to prevent loss. However, in addition to creating

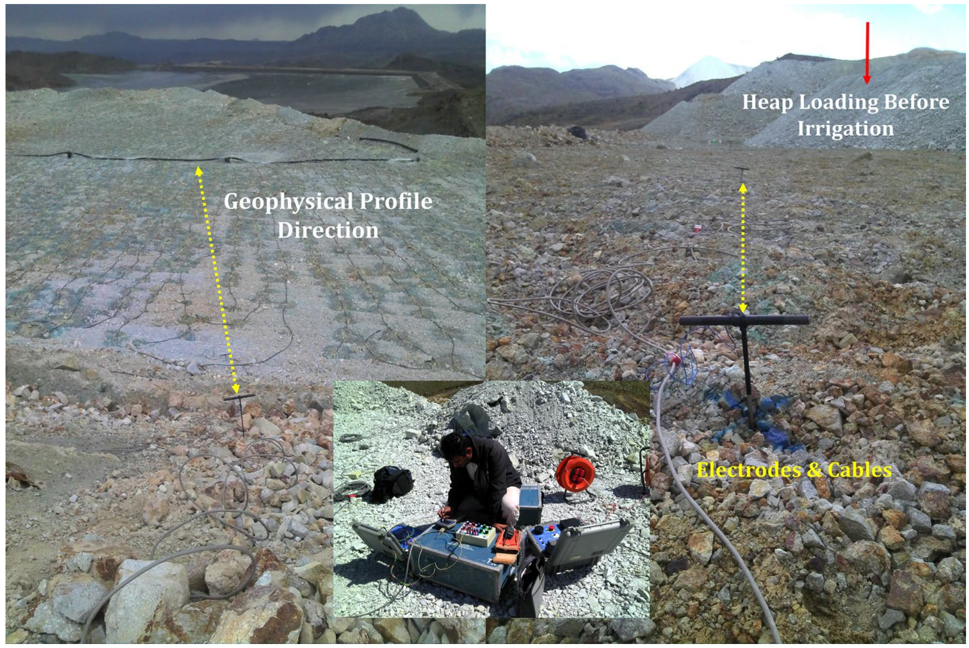

Fig. 7 General view of heap structure, geophysical instruments, profile orientation and electrode type

instability on the eastern slope and increasing the risk of heap failure, this fluid leakage means that the leachate solution from lifts 4 and 5 will not penetrate to deeper lifts, resulting in retention of copper at lower depths where it cannot be extracted. The intent of this geophysical investigation was to locate such unleached copper zones within the heap and the preferential flow paths, fluid leakage locations, and high moisture zones on the eastern slope, as well as detecting segments with a high possibility of failure and slope instability.

Fig. 8 Seepage of PLS from the eastern slope of the heap, resulting in geotechnical hazards and loss of dissolved copper

Hydrogeophysics as a Tool in Characterization of Coupled Processes in Heap Leaching

The high amount of electrically conductive acid on the heap surface reduces signal strength, shortens current paths, and reduces depth penetration of the IP signal. Since the IP method is very sensitive to the signal/noise ratio, the IP data are only valid in the upper parts of the heap; excessive noise makes the results useless for deeper zones. The RES data were therefore used instead to characterise the heap and to describe the processes occurring within the system.

As illustrated (Fig. 9), RES successfully detected fluid accumulation zones (pools) in the leaching structure. These zones have not been well investigated in previous heap leaching structure studies, but can have a critical effect on the creation of preferential flow paths in the heap. These pooling zones and preferential flow paths prevent some locations from being efficiently washed, which decreases metal recovery.

A two-dimensional (2-D) inverted resistivity model was developed along profile P1 (Fig. 9). Inversion modeling was conducted through simultaneous use of the pole–dipole and dipole–dipole data; the dipole–dipole data preserved the high resolution of the surficial response while the pole–dipole data provided the desired depth range. A single application of the dipole–dipole array with a 10 m electrode spacing could only provide an image to an approximate depth of 25 m. Since the geo-membrane liner in the Miduk heap leaching structure lies 35 m below the ground surface, this means that it cannot e used to acquire liner information. Using a mixed array through inversion modeling increased

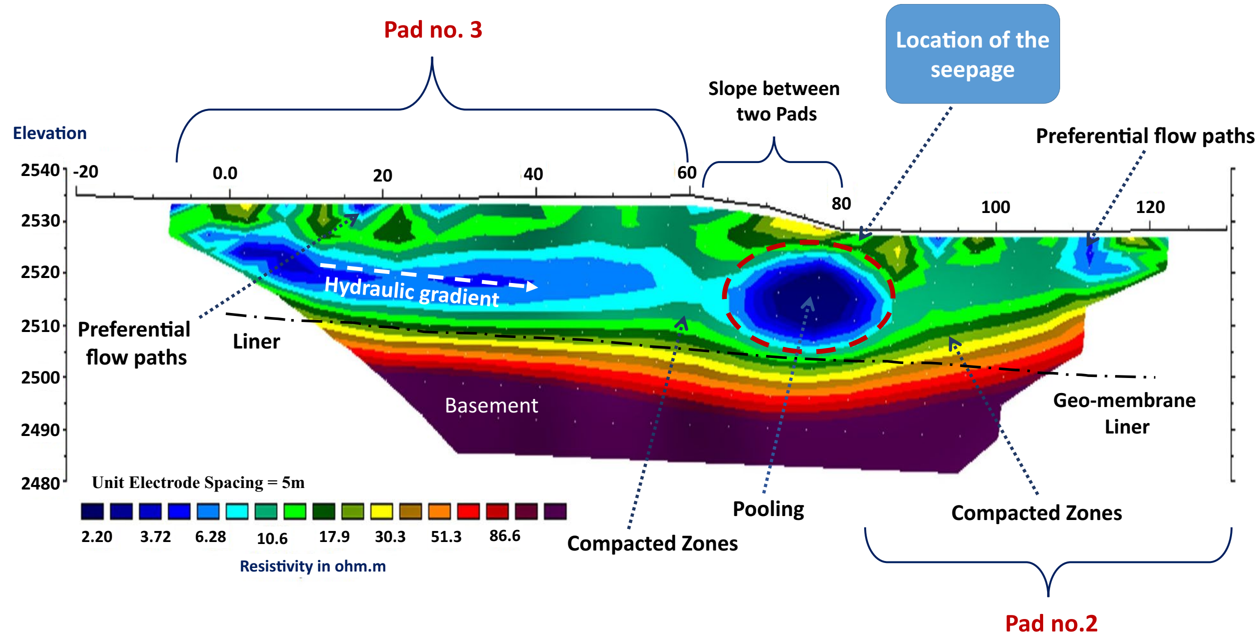

Fig. 9 Two-dimensional inverted resistivity model along the profile P1 (showing hydraulic gradient, basement, geomembrane liner, pooling location and the slope between Pad-2 and Pad-3)

the search depth to 50 m. The pole–dipole array was conducted in backward and forward modes to provide suitable accuracy, as a single one-way performance mode of the pole–dipole method would lead to anomaly displacement, and therefore to reduced accuracy in the exact locations of interest.

As Fig. 9 shows, the wall leakage zones, location of the geo-membrane liner, preferential flow paths, and the compacted zones were clearly detected. Using the resistivity range, one can see that locations in blue, with low resistivity values (less than 6 Ω-m), are highly concentrated with acid, and are probably the fluid flow paths through which the copper is washed from the ore and transported to the PLS collection system. The higher resistivities, in green, orange, and red, likely show less washed locations. The basement rock is distinct, and displays a very high resistivity due to its rocky characteristics, lack of fluids, and the presence of a nonconductive geomembrane liner beneath the heap.

The fluid accumulation locations, where significant volumes of acid have pooled, can create preferential fluid flow paths, increase heap instability, and induce leakage problems (Fig. 9). This issue poses significant challenges for mining and production engineers who are responsible for preventing pooling in heap structures (for example, through dynamic control of the irrigation rate or the arrangement of emitters over the heap). The other issue that should be addressed is the presence of low resistivity zones, especially on the slopes between the pads, as these probably represent low moisture content areas. One possible approach that could be investigated for preventing pooling is irrigation of these areas. As shown in Fig. 10, the presence of a dry zone in the northern part of the pooling zone is an important factor in the development of a leakage zone on the eastern slope. The relationship between these zones is governed by the relative differences in hydraulic conductivity (Fig. 3). In the dry zone, under a high matrix suction, the hydraulic conductivity will be less than in zones of higher water content; thus flow will preferentially be focussed within the wetter zones, potentially inducing leakage.

The geophysical profiles also revealed these locations of preferential flow and leakage. The field investigation on the eastern slope of the heap not only verified the locations where leakage was occuring (Fig. 8), but also detected other segments with high moisture levels and cracks that could cause geotechnical instability and wall failure.

Table 2 provides the chemical analysis of a leakage water sample from the east slope of the heap. The copper concentration is high (1624 ppm), the pH is low (≈ 1.6), and the sulphur content is extremely high (22,590 ppm). In these parts of the heap, the irrigated acid on lifts 4 and 5 of Pad 3 (the green part of Fig. 10, below the seepage zone) does not penetrate into the lower lifts of the heap, which reduces leaching efficiency; thus, significant amounts of copper remain in these lifts. The high dissolved copper concentration found in the output PLS solution also indicates that if the leakage from the wall is not properly controlled, it will be environmentally dangerous. Low resistivity values in geophysical profiles, however, are locations where the existing solution is

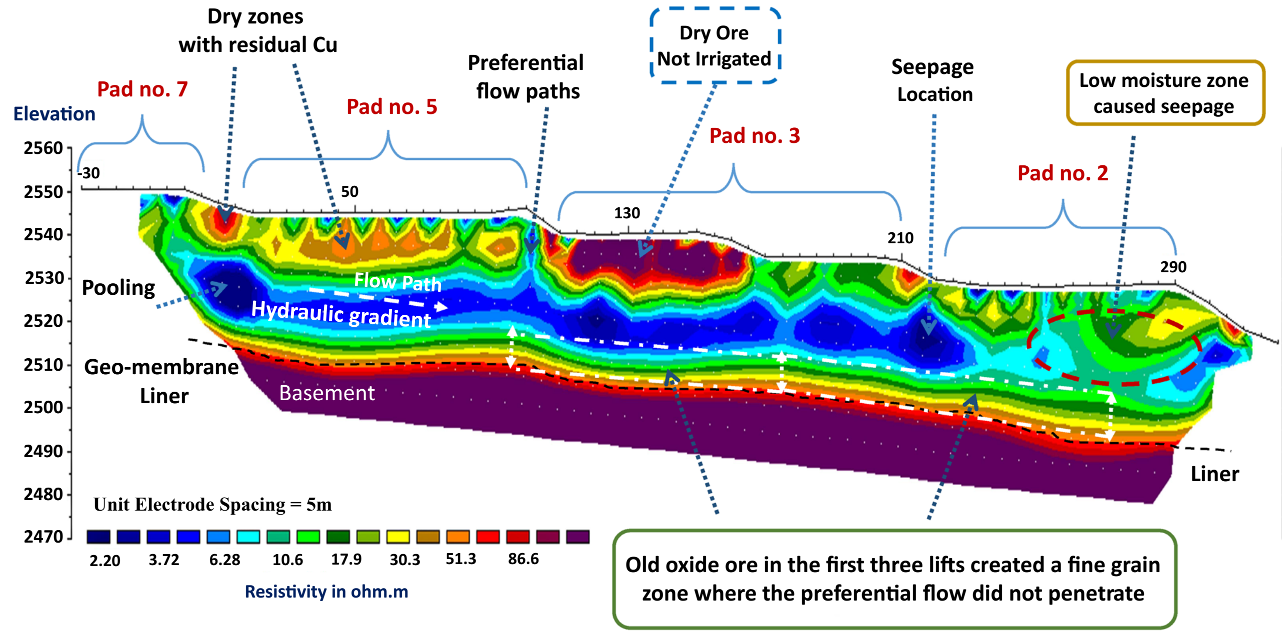

Fig. 10 Two-dimensional inverted resistivity model along profile P2; showing poorly irrigated areas, preferential flow paths and fine-grain oxide zones

Table 2 Chemical analysis of a leakage water sample from the east wall of the heap showing a chemical composition similar to that of PLS

Parameter	Value	Parameter	Value (ppm)	Parameter	Value (ppm)	Parameter	Value
pH	1.605	Cu	1624	HCO_3	< 1	Cd	1.87 ppm
Eh	508.5 mv	Ca	465	CO_3	< 1	Co	11.3 ppm
EC	53.65 µS	K	24.08	F	166	Cr	2.41 ppm
T	18.3 °C	Na	121.7	Cl	33	P	125 ppm
Salinity	36.65 ppt	Mg	4540	Br	92	S	22,590 ppm
DO	23.1%	Fe	4130	SO_3	< 10	As	15.6 ppm
DO	1.8 mg/L	Mn	113.2	SO_4	17,000	Li	1.23 ppm
Flux	25.4 L/min	Al	9230	NO_2	< 10	La	65.4 ppb
		Mo	0.45	NO_3	45	Sr	1.41 ppm
		Ni	10.5	PO_4	< 10	U	1.37 ppm
		Ti	4.7			Th	134.7 ppb

highly acidic with a high copper content, and where copper concentrations in the remaining soil are expected to be very low. Thus, hydrogeophysical investigation of the leaching structures can be used to maintain operational efficiency.

The other advantage of electrical resistivity is that one can use it to detect copper in unleached zones within the heap. Therefore, in this study, profile P2 was designed to extend over some parts of Pad 3 that were still being loaded. In Fig. 10, these parts have been labeled as “Dry Ore, Not Irrigated”, and indicate how resistivity varies with the moisture content and the amount of leaching in each part of the heap structure. The resistivity of the dry soil is as high as 86 Ω-m in some areas, which suggests that these locations should be essentially dry and un-leached. Areas with resistivities of less than 6 Ω-m likely reflect zones that are completely leached and acid-saturated. Dry zones with high resistivity values, however, are locations where copper remains and are responsible for the low metal recovery of the heap leaching.

As shown in Fig. 10, the three initial lifts of the Miduk heap were loaded by dumps of fine-grained soils and oxidized particles with a high clay content, while the next lifts were a mixture of coarser sulphide soils. Because the oxide materials react more with acid, their structure degrades over time, leaving finer particles with less permeability. This has created a fine-grained, consolidated zone in the lifts close to the liner, and prevents acid irrigation from reaching some parts of the pile. Instead, the acid has migrated over these zones toward the downstream PLS pool. As discussed above, the relative fluid fluxes in different parts of the heap depend on the irrigation rate. Hence, the different moisture content between two adjacent lifts and the irrigation rate are the main factors causing flow bypass around the older oxide ore (in the first three lifts). In general, dynamic control of the irrigation rate is important for managing the heap leaching structures.

A 3-D resistivity model was built for Pad 5 using the geophysical data measured along the three profiles of P3, P4, and P5 (Fig. 11). Using this approach, the relationships between the resistivity and each effective operational parameter were correlated to create a three-dimensional model for the entire heap. Each section of the model represents a resistivity change at a specific depth in Pad 5.

As shown in the 3-D image of Fig. 11, the depth of the fluid accumulation zone increases to approximately 15 m in the eastern wall (the right side of the image). This is the main reason for increased moisture on the eastern slope of the heap. Furthermore, zones with high resistivity values can be seen at a depth of about 30 m below the surface, which are probably due to the three initial lifts next to the geo-membrane liner.

By determining correlating resistivity with parameters such as fluid accumulation, copper grade, and slope stability, geophysics can be indirectly used to define the important operational parameters of the heap leaching structures. Figure 12 shows the two-dimensional inverted resistivity model (tomographic section) along profile P3 of Pad 5. The results were compared with a mathematical model presented by Wu et al. (2010) for the extracted copper from an idealised heap. According to their model, the contour maps of different parameters in a heap section are similar to those shown in Fig. 12. The lower right edge of the section was predicted to have higher ferric iron concentrations, greater amounts of extracted copper, greater oxygen content, and higher temperatures. Our results agree with these findings and show higher electrical conductivity in this zone.

Conclusion

Hydrogeophysical investigations were shown to be helpful in identifying the hydraulic, geotechnical and chemical parameters of an active heap leaching structure. Monitoring and dynamic control of these parameters can increase the performance and recovery of heap leaching, increase the PLS concentrations, and prevent possible geotechnical problems and environmental impacts. In this study, which was carried out on the heap leaching site of the Miduk copper mine, locations with residual copper, preferential flow paths, pooling, anomalous geochemical signatures, leakage, and with a high risk of instability were identified.

As most areas of the Miduk heap were only partially saturated and had significant internal fluid fluxes, the IP method had a high level of noise. Low signal strength due to the high hydraulic conductivities and variable streaming potentials were caused by rapid fluid flow, which thus gave a suitable IP response only in the upper few meters of the heap. Simultaneous application of dual-direction pole–dipole arrays and dipole–dipole arrays not only provided high resolution geophysical data, but also resolved the depth limitation h. This mixed array method could be used to characterize underground conditions, perhaps even for leaching structures more than 100 m high by extending the electrode spacing. Accurate field measurements for such heap structures require the use of long steel electrodes, which are often used for geotechnical investigations. On the other hand, in some parts of the heap, where materials had only been recently deposited, resistivities of at least 80 Ω-m revealed dry locations that contain residual copper, whereas resistivities less than 6 Ω-m reflect locations of fluid accumulation.

This study successfully located the fluid leakage zones on the eastern wall of the heap as well as the cracks and geotechnically unstable segments. The study further confirmed that the fine-grained oxide zone in the three initial lifts of the heap prevents further penetration of irrigated fluid to deeper zones. Dynamic monitoring and adjustment of the irrigation rate according to the dynamic moisture content is proposed to overcome this issue.

Several tasks can be carried out to avoid formation of fluid accumulation zones. They include acid irrigation on the slope between pads, mixing soils from different dumps, accurate particle grading during loading, preventing or controlling efflorescence formation from the emitters to ensure uniform irrigation, and separating very large rocks before loading. In addition, dynamic monitoring of the irrigation rate and geophysical monitoring of the degree of saturation in different lifts would help limit formation of preferential flow paths, prevent fluid leakage and pooling, reduce the risk of heap instability, reduce the amount of applied acid, and increase metal recovery.

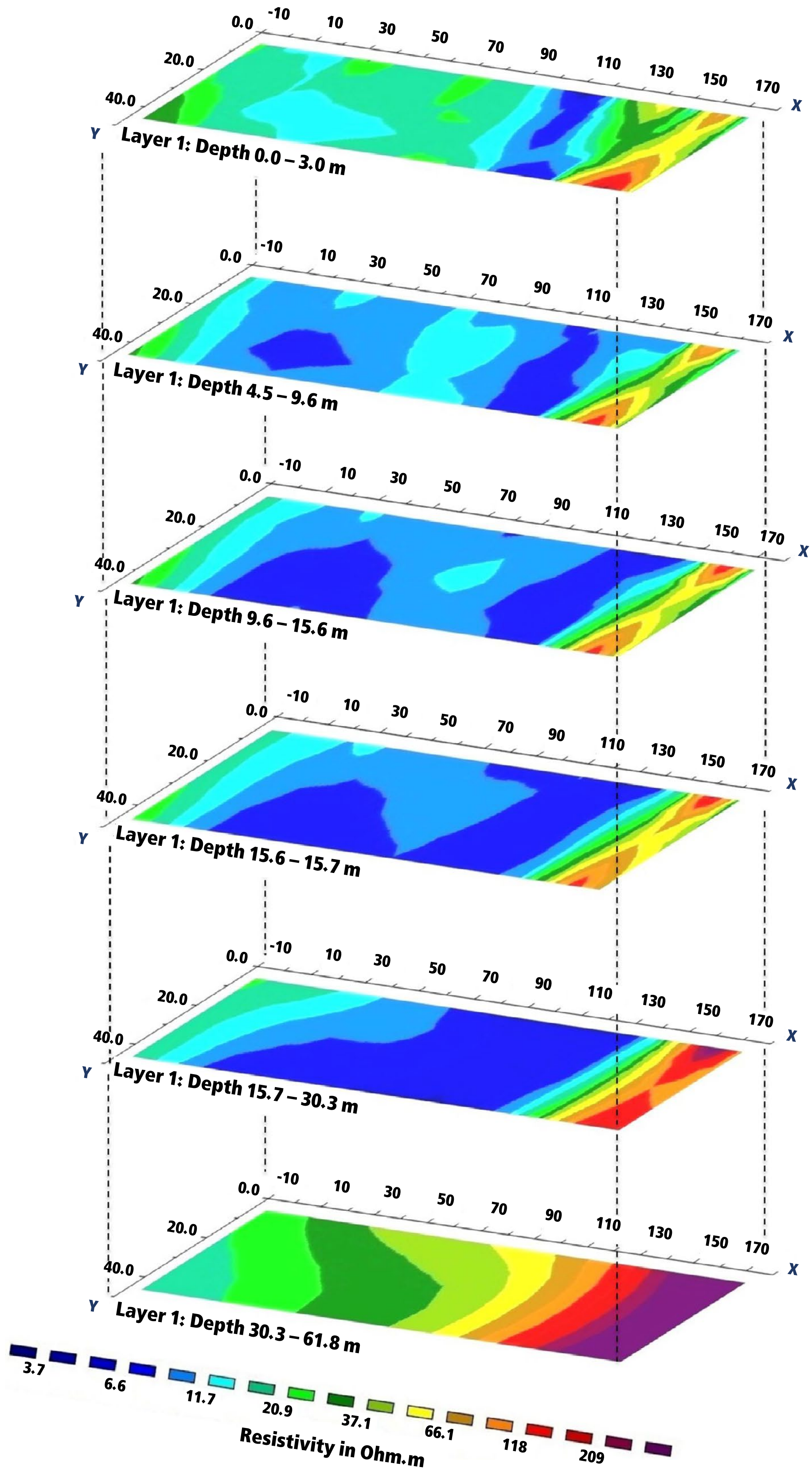

Fig. 11 A three-dimensional resistivity model of Pad 5. Each section represents the resistivity at a specific depth

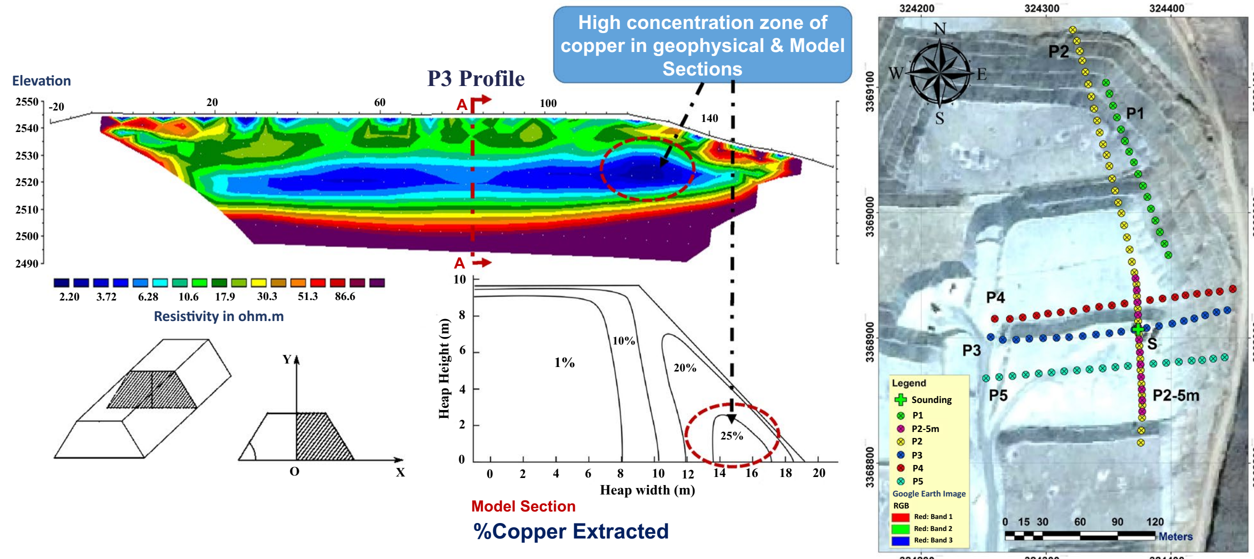

Fig. 12 Two-dimensional inverted resistivity model along profile P3 of Pad 5. A comparison is provided between the geophysical model (upper left) and the model (bottom left) presented by Wu et al. (2010) for copper extraction based on the heap geometry

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